Estimated Probability of Traumatic Chest Injury During an International Space Station Mission

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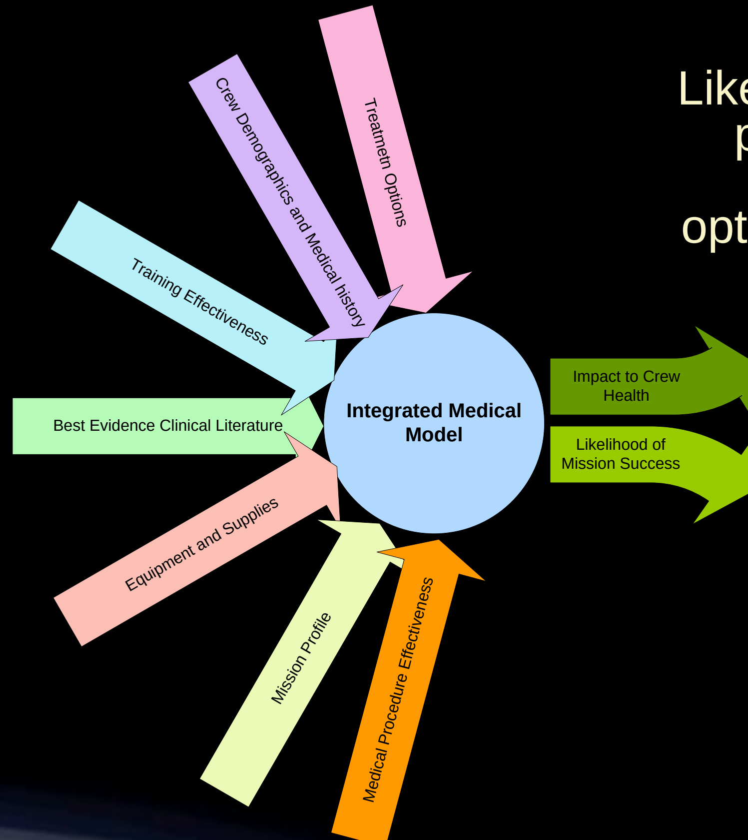
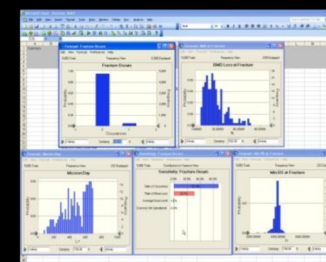
Integrated Medical Model (IMM)

Potential Medical Condition

Evaluate with IMM



Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.



- Probability and consequences of medical risks
- Integrate best evidence in a quantifiable assessment of risk
- Identify medical resources necessary to optimize health and mission success

Probabilistic modeling of rare medical events

- Event has not happened during a space mission
  - No incidence rate
  - Many unknowns
- Construct a computational model
  - Define the initiating event scenario and resulting injury
  - Determine available data and develop parameter distributions
  - Mathematically model the physiological response
  - Perform Verification and Validation
  - Relate the physiological response to probability of injury
  - Determine probability of occurrence
- Use probabilistic risk assessment methodology
  - Monte Carlo simulations
  - Estimate the most likely probability and confidence intervals

Initiating Event Scenario and Injury Definition

- An astronaut translating with equipment too large to see around accidently impacting another astronaut in the chest with attention focused elsewhere

- Traumatic chest injury defined as an injury with an Abbreviated Injury Scale (AIS) score of 3 or higher

AIS definitions for skeletal and soft tissue injuries of the thorax

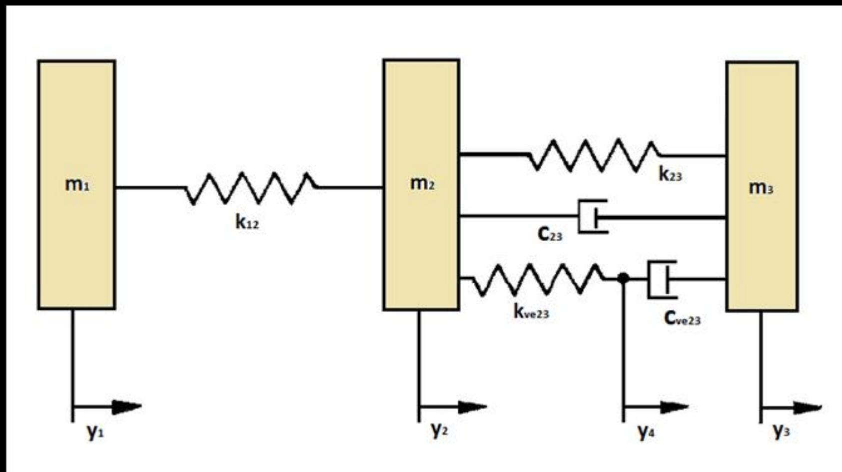
AIS	Injury Severity	Skeletal Injury	Soft Tissue Injury
1	Minor	1 rib fracture	Contusion of bronchus
2	Moderate	2-3 rib fractures Sternum fracture	Partial thickness bronchus tear
3	Serious	4 or more rib fracture on one side 2-3 rib fractures with hemo/pneumothorax	Lung contusion Minor heart contusion
4	Severe	Flail chest 4 or more rib fractures on each side 4 or more rib fractures with hemo/pneumothorax	Bilateral lung laceration Minor aortic laceration Major heart contusion
5	Critical	Bilateral flail chest	Major aortic laceration Lung laceration with tension pneumothorax
6	Maximum		Aortic laceration with haemorrhage not confined to mediastinum

Berthet et al., "Review of the thorax injury criteria," APROSYS AP-SP51-0038-B, 2006.

Parameter distributions

- Astronaut parameters
  - Astronaut mass
  - Chest depth
  - Translational velocity
- Mission parameters
  - ISS equipment masses
- Research data
  - Thorax stiffness and damping characteristics
  - Experimental impact response – normalized compression
  - Injury severity resulting from experimental impacts
- Spaceflight data
  - Impact rate

Biomechanical Model of the Chest



Equations of motion:

$$m_1\ddot{y}_1 + k_{12}y_1 - k_{12}y_2 = 0$$
$$m_2\ddot{y}_2 + C_{23}\dot{y}_2 - C_{23}\dot{y}_3 + (k_{12} + k_{23} + k_{ve23})y_2 - k_{12}y_1 - k_{23}y_3 - k_{ve23}y_4 = 0$$
$$m_3\ddot{y}_3 + (C_{23} + C_{ve23})\dot{y}_3 - C_{23}\dot{y}_2 - C_{ve23}\dot{y}_4 + k_{23}y_3 - k_{23}y_2 = 0$$
$$C_{ve23}\dot{y}_4 - C_{ve23}\dot{y}_3 + k_{ve23}y_4 - k_{ve23}y_2 = 0$$

Initial conditions:

$$y_1(0) = y_2(0) = y_3(0) = y_4(0) = 0$$
$$\dot{y}_1(0) = v_o$$
$$\dot{y}_2(0) = \dot{y}_3(0) = 0$$

Output:

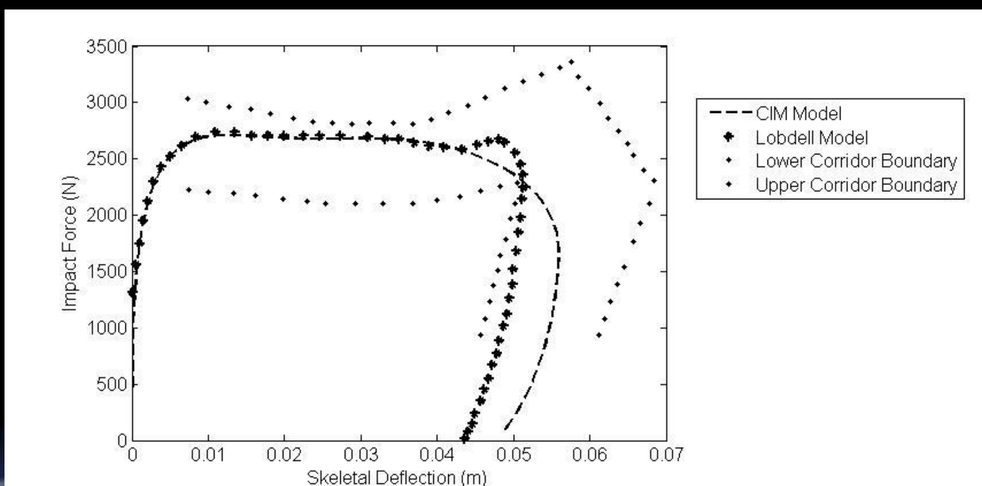
$$d_{skel} = y_2 - y_3$$
$$NC = \frac{d_{skel}}{CD}$$

Parameter Name	Parameter Symbol
Mass of impactor	m_1
Mass of sternum	m_2
Mass of thorax	m_3
Interface between impactor and sternum	k_{12}
Rib cage elasticity	k_{23}
Damping effects of air and blood	c_{23}
Muscle tissue elasticity	k_{ve23}
Muscle tissue viscosity	c_{ve23}
Displacement of m_1	y_1
Velocity of m_1	$\dot{y}_1$
Acceleration of m_1	$\ddot{y}_1$
Displacement of m_2	y_2
Velocity of m_2	$\dot{y}_2$
Acceleration of m_2	$\ddot{y}_2$
Displacement of m_3	y_3
Velocity of m_3	$\dot{y}_3$
Acceleration of m_3	$\ddot{y}_3$
Displacement between k_{ve23} and c_{ve23}	y_4
Velocity between k_{ve23} and c_{ve23}	$\dot{y}_4$
Initial velocity	v_o
Chest deflection	d_{skel}
Normalized compression	NC
Chest depth	CD

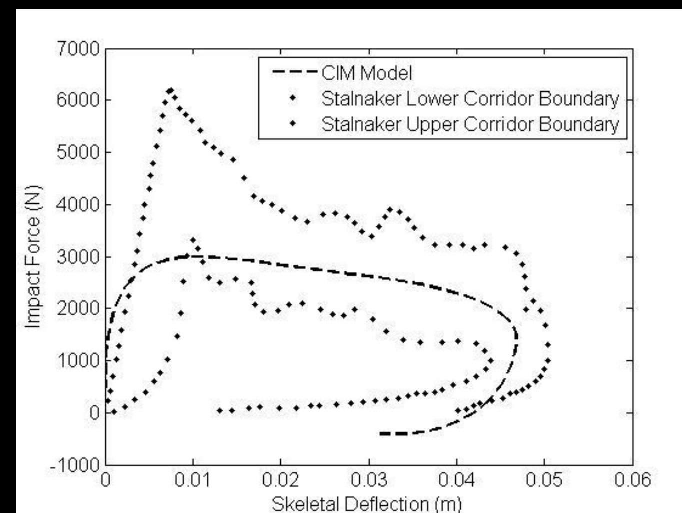
Viano, "Biomechanics of chest and abdomen impact," *Aviat Space Environ Med*, 49(1) , 125-35, 1978.

Biomechanical Model Verification and Validation

- Model output fits within data corridors:
  - Data corridor upon which the model was built (Verification)
  - Data corridor from data set not used to build model (Validation)



C. Kroell, "Thoracic Response to Blunt Frontal Loading," in *The Human Thorax - Anatomy, Injury and Biomechanics* , Warrendale, PA: Society of Automotive Engineers, Inc., 1976.

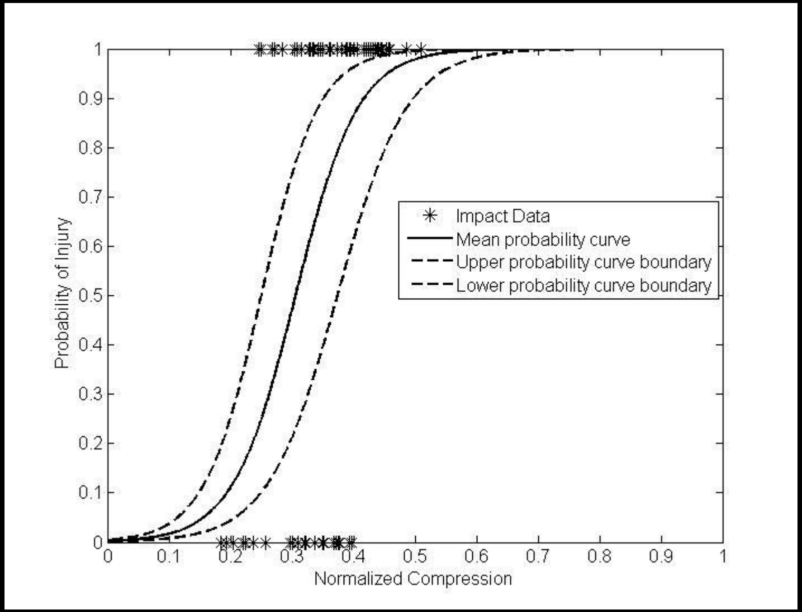


Stalnaker et al., "Human Torso Response to Blunt Trauma," in *Human Impact Response Measurement and Simulation*. New York, NY: Plenum Press, 1973.

Probability of Injury

- Translation between normalized compression and injury probability
  - Normalized compression and AIS score from several impact studies were used
  - A 0 was given to an AIS of 2 or lower, a 1 was given to an AIS of 3 or higher (Data points in graph)
  - Matlab's glmfit was used to find the logistic regression coefficients (A & B) for the probability equation, A = -6.06 ± 10%, B = 19.75 ± 10%
  - The probability equation is:

$$P_{Injury}(NC) = \frac{1}{1 + e^{-(A+B*NC)}}$$



Viano, "Biomechanics of chest and abdomen impact," *Aviat Space Environ Med*, 49(1) , 125-35, 1978.

Kroell et al.. "Impact tolerance and response of the human thorax II,", SAE Paper No. 741187, 1974.

Kroell, "Thoracic Response to Blunt Frontal Loading," in *The Human Thorax - Anatomy, Injury and Biomechanics* , Warrendale, PA: Society of Automotive Engineers, Inc., 1976.

Yoganandan et al., "Thoracic deformation and velocity analysis in frontal impact," *J. Biomech. Eng*, 117(1), 48-52, 1995.

Probability of Impact

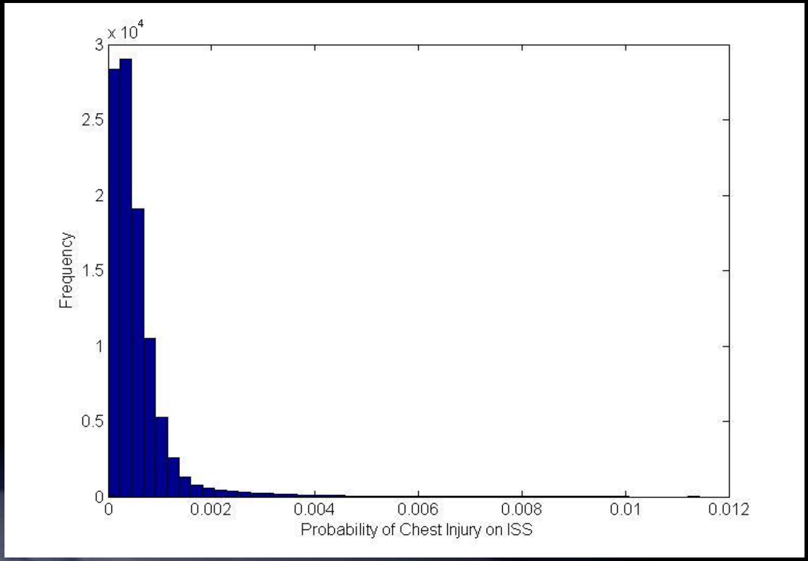
- Ideally, we would use a rate of the number of times an astronaut accidently impacts a piece of equipment with his or her chest during a mission
- However, this data does not exist
- Instead, we know there have been 6 minor trunk injuries in 26.4 years of flight and 0 traumatic chest injuries
- Since an impact must have occurred to cause the minor injuries, we it as our impact rate
- The impact rate (λ) is developed as an uniform distribution with 6/26.4 impacts/person*year as the maximum value and 0/26.4 impacts/person*year as the minimum value
- The impact probability equation is:

$$P_{Impact}(\lambda) = 1 - e^{-\lambda}$$

Scheuring et al, "Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts," *Aviat Space Environ Med*, 80(2), 117-24, 2009.

Results

- Probability of impact and probability of injury are multiplied to obtain probability of traumatic chest injury
- 100,000 Monte Carlo simulation trials performed to obtain most likely probability of traumatic chest injury



Distribution	Mean	Standard Deviation	5%	95%
Total Injury Probability	5.32×10^{-4}	5.95×10^{-4}	4.16×10^{-5}	1.39×10^{-3}

Sensitivity Analysis

- Impactor velocity and rate of impact are the two most sensitive parameters in the model
- Better estimates of these values could reduce the uncertainty in the probability estimate

Parameter Name	% Contribution to Variance
Velocity of the impactor, $v0$	48.18
Rate of impact, λ	36.22
Probability coefficient, A	13.36
Mass of the impactor, m_1	1.89
Probability coefficient, B	0.279
Damping constant, c_{23}	0.031
Spring constant, k_{23}	0.024
Astronaut Mass, AM	0.0042
Sternum mass, m_2	0.0042
Thorax mass, m_3	0.0042
Chest depth, CD	0.0042
Damping constant, c_{ve23}	0.0001
Spring constant, k_{12}	0.000008
Spring constant, k_{ve23}	0.000007

Conclusions

- A computational model has been developed to predict the probability of traumatic chest injury on ISS
- The risk is uncertain because the medical event hasn’t happened, but the model bounds this uncertainty
- The estimated probability of traumatic chest injury is small, but the impact to the mission could be significant if it were to happen
- These results have been incorporated into the parent Integrated Medical Model and assessed relative to other potential medical events

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